Exhibit A

Peltier-Seebeck effect

From Wikipedia, the free encyclopedia.

The **Peltier-Seebeck effect**, or **thermoelectric effect**, is the direct conversion of heat differentials to electric voltage and vice versa. Related effects are the **Thomson effect** and Joule heating. The Peltier-Seebeck and Thomson effects are reversible (in fact, the Peltier and Seebeck effects *are* reversals of one another); Joule heating is not, and cannot be, under the laws of thermodynamics.

Contents

Seebeck effect

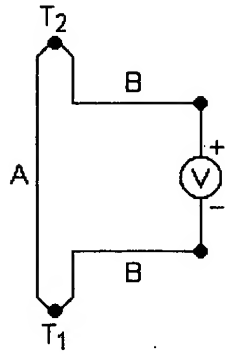
The **Seebeck effect** is the conversion of heat differences directly into electricity.

This effect was first discovered, accidentally, by the Estonian physicist Thomas Johann Seebeck in 1821, who found that a voltage existed between two ends of a metal bar when a temperature gradient ∇T existed in the bar.

He also discovered that a compass needle would be deflected when a closed loop was formed of two metals with a temperature difference between the junctions. This is because the metals respond differently to the heat difference, which creates a current loop, which produces a magnetic field.

A voltage, the thermoelectric EMF, is created in the presence of a temperature difference between two different metals or semiconductors. This usually causes a continuous current to flow in the conductors. The voltage created is on the order of several μV per kelvin (or degree Celsius) of difference.

In the circuit:



(which can be in several different configurations and be governed by the same equations), the voltage developed can be derived from:

$$V = \int_{T_1}^{T_2} \left(S_B(T) - S_A(T) \right) \, dT$$

S_A and S_B are the Seebeck coefficients (also called *thermoelectric power* or *thermopower*) of the metals A and B, and T_1 and T_2 are the temperatures of the two junctions. The Seebeck coefficients are non-linear, and depend on the conductors' absolute temperature, material, and molecular structure. If the Seebeck coefficients are effectively constant for the measured temperature range, the above formula can be approximated as:

$$V = (S_B - S_A) \cdot (T_2 - T_1)$$

Thus, a thermocouple works by measuring the difference in potential caused by the dissimilar wires. It can be used to measure a temperature difference directly, or to measure an absolute temperature, by setting one end to a known temperature. Several thermocouples in series are called a thermopile.

This is also the principle at work behind thermal diodes and thermoelectric generators (such as radioisotope thermoelectric generators or RTGs) which are used for creating power from heat differentials.

The Seebeck effect is due to two effects: *charge carrier diffusion* and *phonon drag*.

Thermopower

If the temperature difference between the two nodes is small,

$$T_2 = T_1 + \Delta T$$

and a voltage ΔV is seen at the terminals, then the thermopower of the entire thermocouple is defined as:

$$S_{AB} = S_B - S_A = \lim_{\Delta T \to 0} \frac{\Delta V}{\Delta T}$$

This can also be written in relation to the electric field E and the temperature gradient ∇T, by the equation

$$S = \frac{E}{|\nabla T|}$$

Superconductors have zero thermopower, and can be used to make thermocouples. This allows a direct measurement of the thermopower of the other material, since it is the thermopower of the entire thermocouple as well.

In semiconductors the sign of the thermopower is used to decide whether the charge carriers are electrons or holes.

Charge carrier diffusion

Charge carriers in the materials (electrons in metals, electrons and holes in semiconductors, ions in ionic conductors) will diffuse when one end of a conductor is at a different temperature than the other. Hot carriers diffuse from the hot end to the cold end, since there is a lower density of hot carriers at the cold end of the conductor. Cold carriers diffuse from the cold end to the hot end for the same reason.

If the conductor were left to reach equilibrium, this process would result in heat being distributed evenly throughout the conductor (see heat transfer). The movement of heat (in the form of hot charge carriers) from one end to the other is called a heat current. As charge carriers are moving, it is also an electrical current.

In a system where both ends are kept at a constant temperature relative to each other (a constant heat current flows from one end to the other), there is a constant diffusion of carriers. If the rate of diffusion of hot and cold carriers were equal, there would be no net change in charge. However, the diffusing charges are scattered by impurities, imperfections, and lattice vibrations (phonons). If the scattering is energy dependent, the hot and cold carriers will diffuse at different rates. This creates a higher density of carriers at one end of the material, and the distance between the positive and negative charges produces a potential difference; an electrostatic voltage.

This electric field, however, opposes the uneven scattering of carriers, and an equilibrium is reached where the net number of carriers diffusing in one direction is canceled by the net number of carriers moving in the opposite direction from the electrostatic field. This means the thermopower of a material depends greatly on impurities, imperfections, and structural changes (which often vary themselves with temperature and electric field), and the thermopower of a material is a collection of many different effects.

Phonon drag

Phonons are not always in local thermal equilibrium; they move along the thermal gradient. They lose momentum by interacting with electrons (or other carriers) and imperfections in the crystal. If the phonon-electron interaction is predominant, the phonons will tend to push the electrons to one end of the material, losing momentum in the process. This contributes to the already present thermoelectric field. This contribution is most important in the temperature region where phonon-electron scattering is predominant. This happens for

$$T \approx \frac{1}{5}\theta_D$$

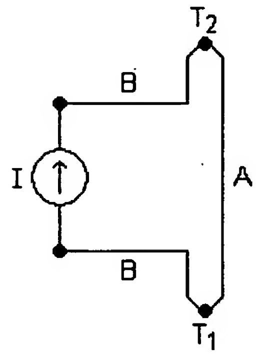
where θ_D is the Debye temperature. At lower temperatures there are less phonons available for drag, and at higher temperatures they tend to lose momentum in phonon-phonon scattering instead of phonon-electron scattering.

This region of the thermopower versus temperature function is highly variable under a magnetic field.

Peltier effect

The **Peltier effect** is the reverse of the Seebeck effect; a creation of a heat difference from an electric voltage.

It occurs when a current is passed through two dissimilar metals or semiconductors (n-type and p-type) that are connected to each other at two junctions (Peltier junctions). The current drives a transfer of heat from one junction to the other: one junction cools off while the other heats up; as a result, the effect is often used for thermoelectric cooling. This effect was observed in 1834 by Jean Peltier, 13 years after Seebeck's initial discovery.



When a current I is made to flow through the circuit, heat is evolved at the upper junction (at T_2), and absorbed at the lower junction (at T_1). The Peltier heat absorbed by the lower junction per unit time, $\dot{Q}$ is equal to

$$\dot{Q} = \Pi_{AB} I = (\Pi_B - \Pi_A)\, I$$

Where Π is the Peltier coefficient Π_{AB} of the entire thermocouple, and Π_A and Π_B are the coefficients of each material. P-type silicon typically has a positive Peltier coefficient (though not above ~550 K), and n-type silicon is typically negative.

The conductors are attempting to return to the electron equilibrium that existed before the current was applied by absorbing energy at one connector and releasing it at the other. The individual couples can be connected in series to enhance the effect.

The direction of heat transfer is controlled by the polarity of the current, reversing the polarity will change the direction of transfer and thus the sign of the heat absorbed/evolved.

A **Peltier cooler**/heater or thermoelectric heat pump is a solid-state active heat pump which transfers heat from one side of the device to the other. Peltier coolers are also called *Thermo Electric Converters* (TEC).

Thomson effect

Thomson effect, named for William Thomson, 1st Baron Kelvin, describes the heating or cooling of a current-carrying conductor with a temperature gradient.

Any current-carrying conductor, with a temperature difference between two points, will either absorb or emit heat, depending on the material.

If a current density J is passed through a homogeneous conductor, heat production per unit volume is

$$q = \rho J^2 - \mu J dT/dx$$

where

ρ is the resistivity of the material

dT/dx is the temperature gradient along the wire

μ is the Thompson coefficient.

The first term ρ J is simply the Joule heating, which is not reversible.

The second term is the Thomson heat, which changes sign when J changes directions.

The Peltier and Seebeck coefficients are related by the Thomson relation

$$\Pi = S \cdot T$$

which predicted the Thomson effect before it was actually formalized. It can also be written

$$\mu = T dS/dT$$

where T is the absolute temperature of the metal.

In metals such as zinc and copper, which have a hotter end at a higher potential and a cooler end at a lower potential, when current moves from the hotter end to the colder end, it is moving from a high to a low potential, so there is an evolution of energy. When it moves from the colder to the hotter end, there is an energy absorption. This is called the **positive Thomson effect**.

In metals such as cobalt, nickel, and iron, which have a cooler end at a higher potential and a hotter end at a lower potential, when current moves from the hotter end to the colder end, it is moving from a low to a high potential, there is an absorption of energy. When it moves from the colder to the hotter end, there is an energy evolution. This is called the **negative Thomson effect**.

In lead, there is zero Thomson effect.

The Seebeck effect is actually a combination of the Peltier and Thomson effects.

See also

- Thermoelectricity
- Joule's law
- Heat transfer
- Thermoelectric cooling
- Pyroelectric effect - the creation of an electric field in a crystal after uniform heating

Patents

- U.S. Patent 2510397 (http://patft.uspto.gov/netacgi/nph-Parser?patentnumber=2510397) - Clarence W. Hansell - "*Heat-to-electrical energy converter*".
- U.S. Patent 2881384 (http://patft.uspto.gov/netacgi/nph-Parser?patentnumber=2881384) - Lyndon A. Durant - "*Thermal electric alternator*"
- U.S. Patent 2915652 (http://patft.uspto.gov/netacgi/nph-Parser?patentnumber=2915652) - G. N. Hatsopoulos - "*Conversion of thermal energy into electrical energy*".
- U.S. Patent 3175105 (http://patft.uspto.gov/netacgi/nph-Parser?patentnumber=3175105) - John E. Creedon - "*Conversion of heat to electricity*"

References

- Besançon, Robert M. (1985). *The Encyclopedia of Physics, Third Edition*, Van Nostrand Reinhold Company. ISBN 0-442-25778-3

External links

General

- Thermoelectricity, including equations and applications (http://www.nanothermel.org/public_main.htm)
- General (http://www.tf.uni-kiel.de/matwis/amat/elmat_en/kap_2/backbone/r2_3_3.html)
- Has an explanation of carrier diffusion and phonon drag components of thermopower (http://www.insa-lyon.fr/Laboratoires/GEMPPM/TEP/index.htm)

Semiconductors

- A brief explanation (http://www.coolworksinc.com/about_thermoelectric_technology.htm)
- An introduction to thermoelectric coolers (http://www.electronics-cooling.com/Resources/EC_Articles/SEP96/sep96_04.htm)
- The science and materials of thermoelectrics (http://www.its.caltech.edu/~jsnyder/thermoelectrics/science_page.htm)

Metals

- The origin of the thermoelectric potential (http://www.uni-konstanz.de/physik/Jaeckle/papers/thermopower/thermopower.html)

Related

- Directory of Peltier device information (http://www.peltier-info.com/info.html)
- A news article on the increases in thermal diode efficiency (http://www.trnmag.com/Stories/2001/121901/Chips_turn_more_heat_to_power_121901.html)
- A wristwatch powered by thermocouples, using the heat difference between the human body and its surroundings (http://www.sii.co.jp/info/eg/thermic_main.html)

Retrieved from "http://en.wikipedia.org/wiki/Peltier-Seebeck_effect"

Categories: Thermodynamics | HVAC | Electricity

- This page was last modified 18:46, 31 October 2005.